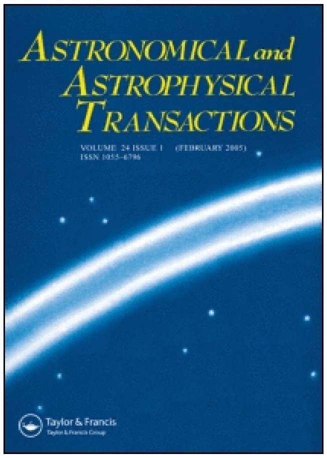

Astronomical & Astrophysical Transactions

The Journal of the Eurasian Astronomical Society

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Radio astronomy of the next century

Yu. N. Parijskij [a]
[a] Special Astrophysical Observatory, N. Arkhyz, Stavzopolskij Region, USSR

Online Publication Date: 01 January 1992
To cite this Article: Parijskij, Yu. N. (1992) 'Radio astronomy of the next century', Astronomical & Astrophysical Transactions, 1:2, 85 - 106
To link to this article: DOI: 10.1080/10556799208244524
URL: http://dx.doi.org/10.1080/10556799208244524

Astronomical and Astrophysical Transactions, 1992,
Vol. 1, pp. 85–106
Reprints available directly from the publisher.
Photocopying permitted by license only

RADIO ASTRONOMY OF THE NEXT CENTURY

YU. N. PARIJSKIJ

Special Astrophysical Observatory, N. Arkhyz, Stavzopolskij Region, 357147 USSR

(7 January 1991)

KEY WORDS Radio astronomy, perspectives

In this contribution we have tried to trace the main trends in the development of the most important parameters of the world's best Radio Telescopes. We examine these trends to the beginning of the next century and predict the level of efficiency that these instruments will reach.

It is shown that rate of growth of the sensitivity, resolution, image quality and other parametres, exponentially increases with time. There has been no sign of slowing over the last 50 years. To reach the predicted level, we expect the appearance of a new generation of Radio Telescopes with a collecting area of about 1 million square meters and with resolution corresponding to the astronomical unit bases. It is suggested that new, much more efficient methods of getting information from the existing telescopes will be realised. This may be done combining the recent developments of ultra high frequency receivers with the computer revolution, and a new understanding of the physical process of image formation.

We compare expected parameters with needs of modern Radio Astronomy, an what kind of fundamental limitation we can have from the physical nature of the objects under exploration and from propagation effects.

After that we have tried to find the possible role of the RATAN-600 in the community of the world's best Radio telescopes, at the beginning of the next century.

First we discuss the limiting parameters of the world's biggest reflector, RATAN-600, and show that only a small fraction of the theoretical potential of that instrument has been realized, up to date. We then collected all suggestions concerning the path to these parameters and selected the first priority list. The list also reflects the box of astrophysical problems matched with the possibilities of the RATAN-600 after realization of the list.

A new epoch of Radio Astronomy can be opened if radio telescopes in the Ecliptic will act as the aperture synthesis array. 3-dimensional image formation can be done, and interstellar screen can be "moved" into the near field zone to escape from the limitation on the angular sizes of the objects, just as it was done in the Radio Astronomy, in the case of troposphere.

This new quality (and many other extreme parameters) of the next century of Radio Astronomy can be really achieved through the coherent activity of the Radio Astronomy Community. This must be done as quickly as possible, due to exponential growth of the electromagnetic pollution by our civilisation in the solar system.

I. GENERAL TRENDS IN RADIO ASTRONOMY INSTRUMENTATION

I.1 Evolution of the Flux Density Limit of the Best Radio Telescopes With Time (see Figure 1)

It may be approximated by the formula

$$P = A_p e^{-B(T-T_0)}$$

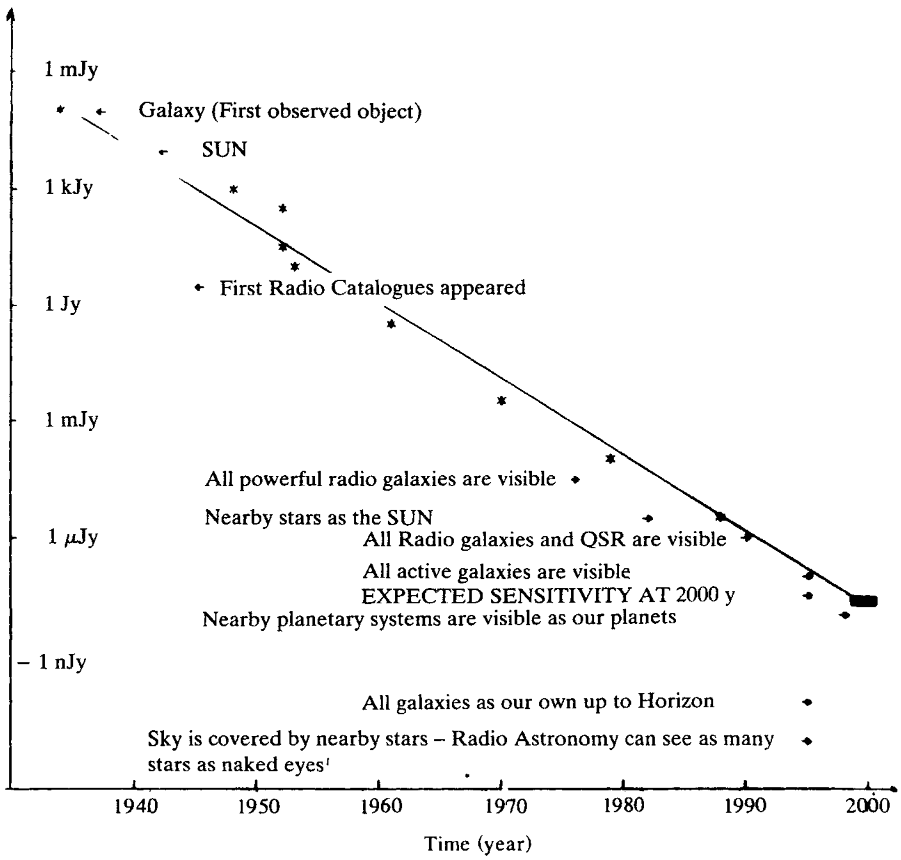

Figure 1 Range of Radio Astronomy and Time.

with $A_p = 10^6$ Jy, $B = 0.46$, T-time in Years, $T_0 = 1932$, Radio Astronomy birthday.

This picture shows that the range of the Radio Astronomy expands exponentially with time (just as the Universe is in the period of inflation!). The most powerful emitters (as active galaxies) may be observed at the end of our century up to the epoch of their formation. Later, less powerful galaxies may be seen up to the horizon and so on. We expect the same story for the Galactic population, which begins and closes our Figure 1.

In the Euclidean Universe, the range of the Radio Telescopes increase by factor 2 every 3 years. It means that for objects which are at a distance more than 3 light years from the Earth, and which are visible by the radio telescope, the signal-to-noise will increase with time even if this object is moving away from us almost at the speed of light! Another prediction may be done for the nearby objects. If we can see objects during three years after the launch, we can see it forever (with the same emiting power on the board). If the object is lost quickly after the launch it must, sooner or later, appear inside the exponentially expanding range of the Radio Astronomy.

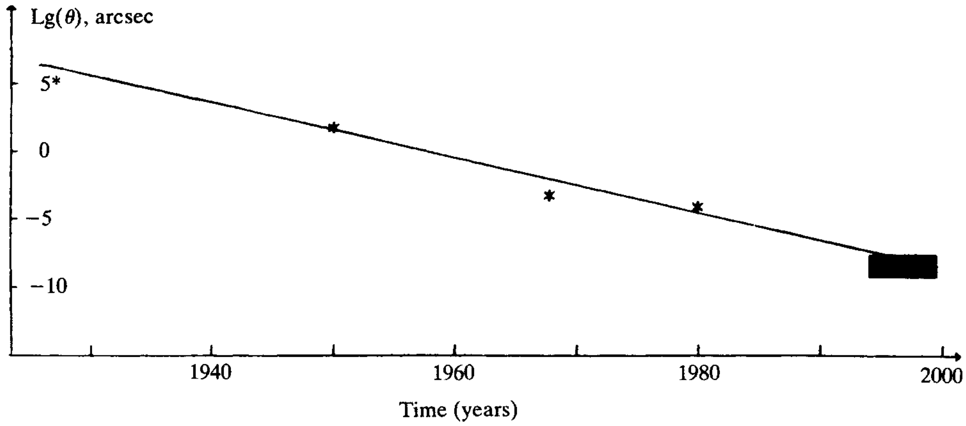

Figure 2 Evolution of the resolving power of Radio Telescopes.

Indeed, if the signal is decreasing as $1/R^2$, $R = vT$, but the sensitivity of the receiving radio telescope is increasing as

$$\Delta P = A \exp(-BT),$$

we always can find T when

$$S/N \gg 1$$

I.2 Evolution of Resolving Power (see Figure 2)

It may be approximated by the expression

$$\theta_{\mathrm{res}} = A_{\mathrm{res}} e^{-B_{\mathrm{res}}(T-T_0)}$$

with $A_{\mathrm{res}} = 1.3 \times 10^5$ arcsec, $B_{\mathrm{res}} = 0.44$, T-current time in years, $T_0 = 1932$.

I.3 Growth of the Collecting Area of the Radio Astronomy Community

It is shown in the Figure 3. Again it may be approximated by the exponential law:

$$\sum = A_\sigma e^{-B_\sigma(T-T_0)}$$

with $A_\sigma = 10\,\mathrm{m}^2$, $B_6 = -0.17$, T-current time in Years, $T_0 = 1932$.

We see that, at the end of this century there will be about 1 million square meters of collecting surface on the Earth available for Radio Astronomy. We hope that radioastronomers can use all this surface as a single giant Radio Telescope (if necessary).

We have mentioned radio telescopes which were built for Radio Astronomy. In the next century, new kinds of the Radio Amateurs may appear—people owning a TV and PC can be organised through the VIDEO-NET, which is just appearing in USA and Japan for the purpose of broad band communication between users and a huge computer. There are more than 100,000,000 TV-users on the Globe with λ^2 collecting area each . . . . The USA is now discussing construction of a

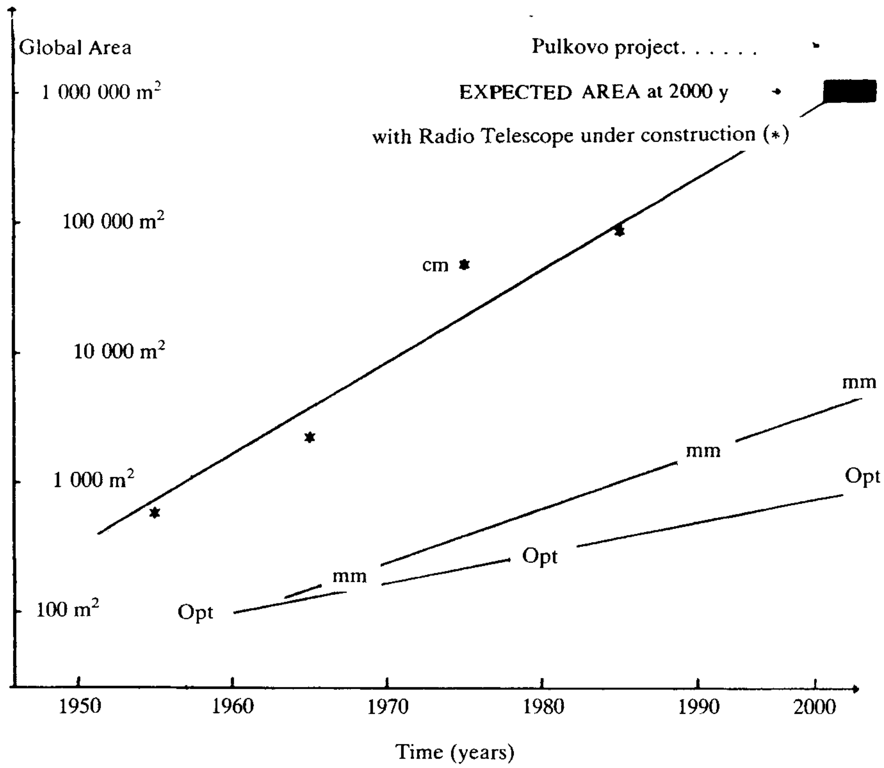

Figure 3 Growth of the collecting area of Radio Telescopes.

new generation of telescopes with collecting surface about 200,000 m^2 at cm-wavelength, 20,000 m^2 at mm wavelengths, and 2000 m^2 at the wavelength below 1 mm (see Section III). This includes new Ground and Space radio telescopes and the upgrading of existing ones as well.

I.4 Evolution of Brightness Temperature Sensitivity

It is shown in the Figure 4, and may be approximated by

$$\Delta T = A_t e^{-B_t(T-T_0)}$$

with $A_b = 390$ K, $B_t = 0.31$, T-current time in years, $T_0 = 1932$.

In Figure 4 we have used the best records on the anisotropy of the Cosmic Background emission.

I.5 Evolution of the Accuracy of the Source Position Measurements

From Figure 5 we have:

$$\Delta\alpha, \Delta\delta = A_{\alpha\delta} e^{-B_{\alpha\delta}(T-T_0)}$$

were $A_{\alpha\delta} = 2 \times 10^5$ arcsec, $B_{\alpha\delta} = 0.34$, $T_0 = 1932$.

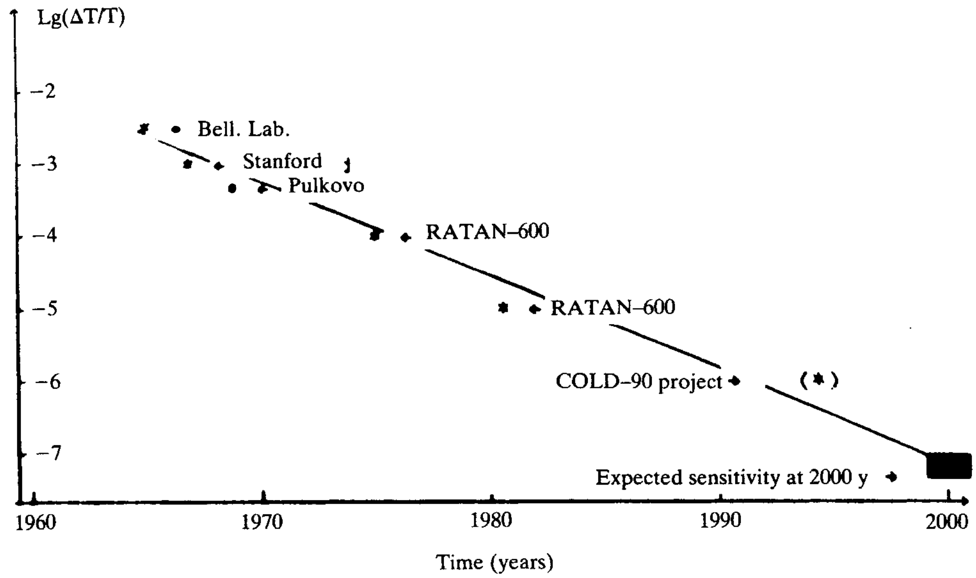

Figure 4 Evolution of the Brightness Temperature Sensitivity (best upper limits on the 3 K anisotropy measurement used).

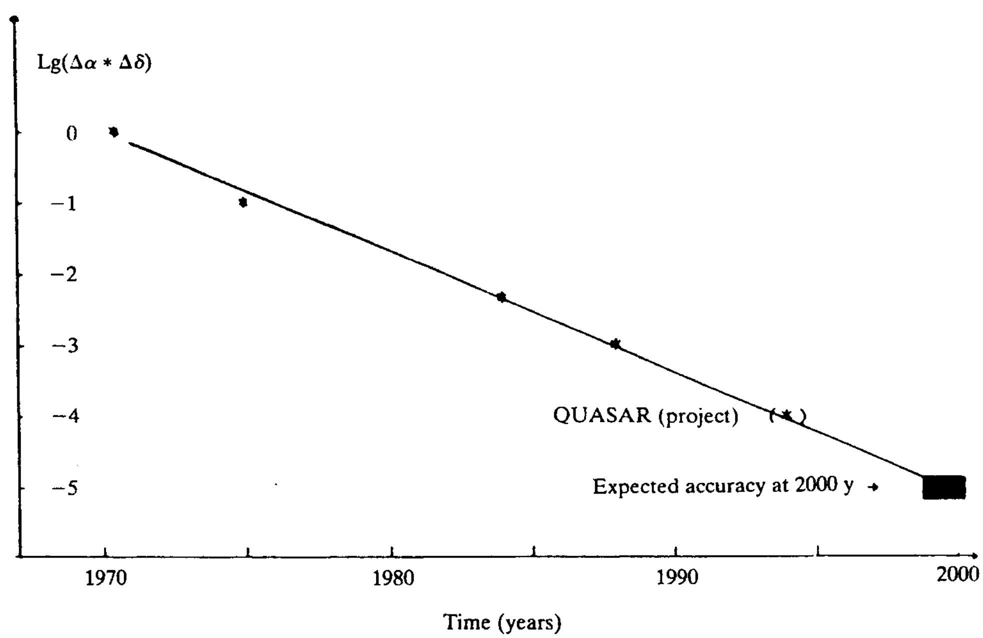

Figure 5 Evolution of the accuracy of the source position measurements.

We have shown the position of the USSR "QUASAR" project on Figure 5. This project will be "just in time."

I.6 Evolution of image quality (dinamical range of the maps)

VLA may be used as the best example. We plot the progress in the dinamical range of this instrument (the ratio of weakest to strongest features on the final map) as a function of time in Figure 6. About 30 db improvement was achieved in 10 years of VLA operation and another 10 db may be found in the next few years, just through better algorithms, and an increase in computer facilities. Maps with better than 1:1 000 000 brightness temperature resolution should appear at the beginning of the next century.

I.7 Evolution of receiver noise

We have used the Arecibo 300m-radio telescope as an example. In Figure 7 the receiver noise temperature is plotted as a function of time. We see that just now the curve crosses the 3K Cosmic Background level. The rate of improvement may be expressed by

$$T_{rec} = A_{rec} e^{-B_{rec}(T - T_0)}$$

where $A_{rec} = 3 \times 10^{-5}$ K, $B_{rec} = 0.2$ ($\lambda = 21$ cm used), $T_0 = 1932$. We may show that at the 2000y, technology will be advanced enough to have receiver noise temperature below sky temperature at all wavelengths, even above the Atmosphere.

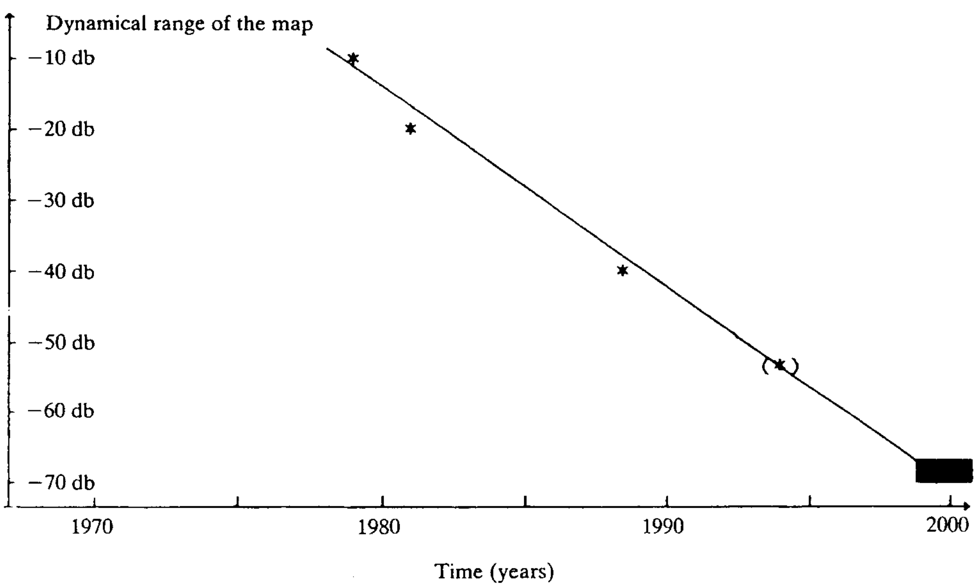

Figure 6 VLA; Progress in the map quality. The ratio of the weakest to the strongest features on the VLA map versus Time.

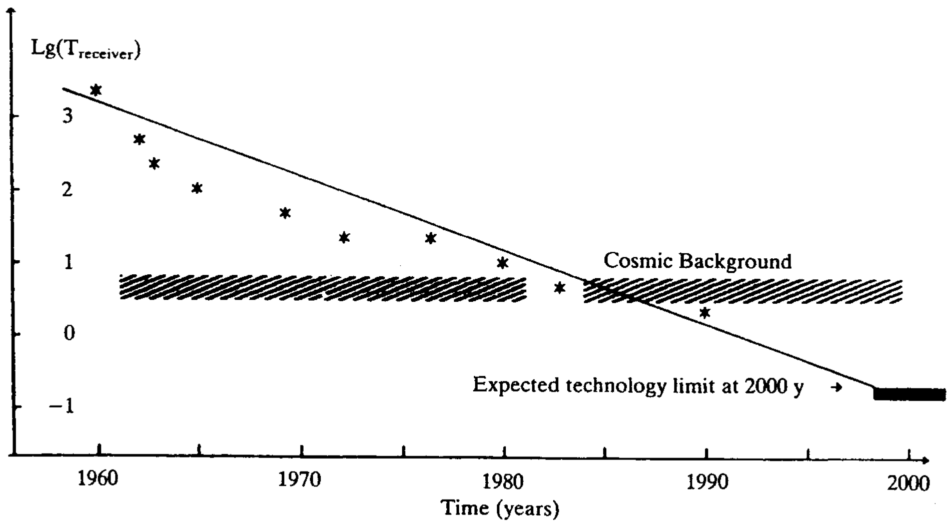

Figure 7 Arecibo Dish. Evolution of the Receiver Noise.

There is some problem with the quantum noise. In usual expression

$$\Delta T = T_{sys}/\sqrt{\Delta \nu \tau}$$

we have to use

$$T_{sys} = h\nu/k.$$

This noise will dominate at wavelengths shorter than 3 mm. It means that having an ideal receiver with T_{rec} (3 K the only way to increase the flux density sensitivity is the construction of the radio telescope with greater collecting surface).

I.8 Progress of the VLBI Technique

Resolution progress was reflected in Figure 2. It is important that there are no technical limits on the Space VLBI. Sensitivity of the VLBI depends on the bandwidth, integration time (coherence time) and on the collecting area of the telescopes. The latter can be traced with the help of Figure 3. We hope that using reference wave front (from natural or artificial source), it is possible to have as long integration time as in the usual single dish observations at the end of this century. Single dish equivalent may be also reached, as far as bandwidth is concerned. (MARK 1, 2, 3, 4 terminals sequence reflects the movements from the fraction of MHz to the GHz bandwidths).

It is very important to show how the VLBI technique crosses the Radio domain and enters the Optical domain in the beginning of the next century. We demonstrate this in Figure 8.

Results discussed in this section are summarized in Table 1.

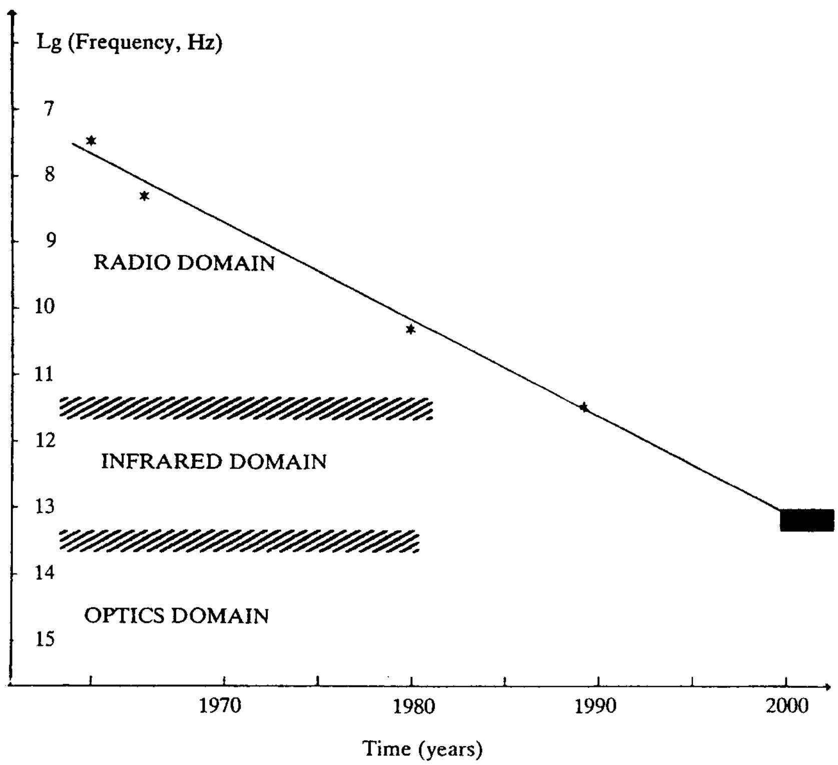

Figure 8 VLBI and Wavelengths.

II. NATURAL LIMITS OF RADIO ASTRONOMY

II. 1

We believe that exponential growth of the resolution, sensitivity, and other parameters of the Radio Telescopes, will hold up to the time when the general exponential evolution of our civilization will stop. But it is interesting to look closer on the limitations settled by Nature itself.

Table 1 Summary on evolution of radio astronomy.

Parameter	*1-year increment*	*Evolution from the beginning*	*Expected level at 2000 y*
Sensitivity	1.5	3×10^{13}	0.03 μJy
Resolution	1.5	1×10^{13}	0.03 μarcsec
Brightness	1.3	1×10^{8}	0.3 μK
Position errors	1.4	1×10^{10}	10 μarsec
Receiver noise	1.2	1×10^{5}	0.3 K
Collecting area	1.2	3×10^{5}	1 million m^2

We shall discuss the following effects:

1. Confusion.
2. Scattering by medium between object and observer.
3. Brightness irregularities of the Sky.
4. Physics of the objects under consideration.

The Confusion limit has been under discussion since 1950. News in this field appeared recently, due to the invasion of flat-inverted-IR-populations of the radio sources. It results in the appearance of well defined optimal frequency where the confusion effect is minimal (for a given resolution). This effect will be shown later.

For all types of instruments, there is an absolute limit of sensitivity (in the flux density and brightness temperature as well) at the wavelength about 1 cm.

For RATAN-600, 1 cm is also the best wavelength, and the sensitivity at this point is limited by a small fraction of μJy (zenith mode). The second news connected with the statement is that μ1 Jy level, the distance between sources will be smaller than their size, and real saturation of the sensitivity may be reached (at any resolution).

Scattering effects are very strong at the meter-wavelengths. In very dense regions (e.g. Sgr-A, point source), even at cm-mm-wavelengths, the visible size may be limited by the interstellar scattering effects. It gives a formal limit on the resolution of the radio telescope (e.g., maximum base for space interferometry is now under discussion). News may come from the near field zone approach, as has happened with the seeing limit from our atmosphere, and recently, with interplanetary scattering effects. Formal limits are shown in Figure 9.

We hope that for the high S/N ratio, it is possible to remove the scattering effects. Brightness temperature limits must be overcome by Nature itself.

Sky irregularity limitations are well known as far as atmosphere emission is concerned. This limit may be overcome by a beam switching mode of observations, multy-frequency operation, water radiometry, or by interferometric methods. For 1-arcsec.resolution, it was demonstrated by VLA groups, for arcmin resolution there is a suggestion to convert single dish into VSA (Very Small Array). RATAN-600 methods involved near-field zone effects Bad news appeared recently from the Galaxy. It was found that even at high latitutes there are irregularities at 1-mK level at 7.6 cm on the 1-degree scale with nonthermal spectrum (RATAN-600 result). Moreover, at short wavelengths, Galactic cirrus emission has irregularities at 10-arcsec-10-arcmin scales with strong inverted spectrum. It means that there is again some optimal wavelength where these limitations are minimal. At present, it seems that this effect will act at short mm-region. At all wave lengths there must be an absolute limit on the brightness temperature sensitivity on all scales settled by predicted 3K-anisotropy at the level between 100-10 μK. New, unpredicted, large scale emitters appeared recently, with a nonthermal spectrum identified with walls of the Void structure. Irregularity of the mm emission of the Galaxy may be caused by the irregularities of the lines emission, even in continuous-type observations.

Physical limitations were discussed many years ago in connection with the Compton threshold on the brightness temperature (10^{12} K) of the synhrotron

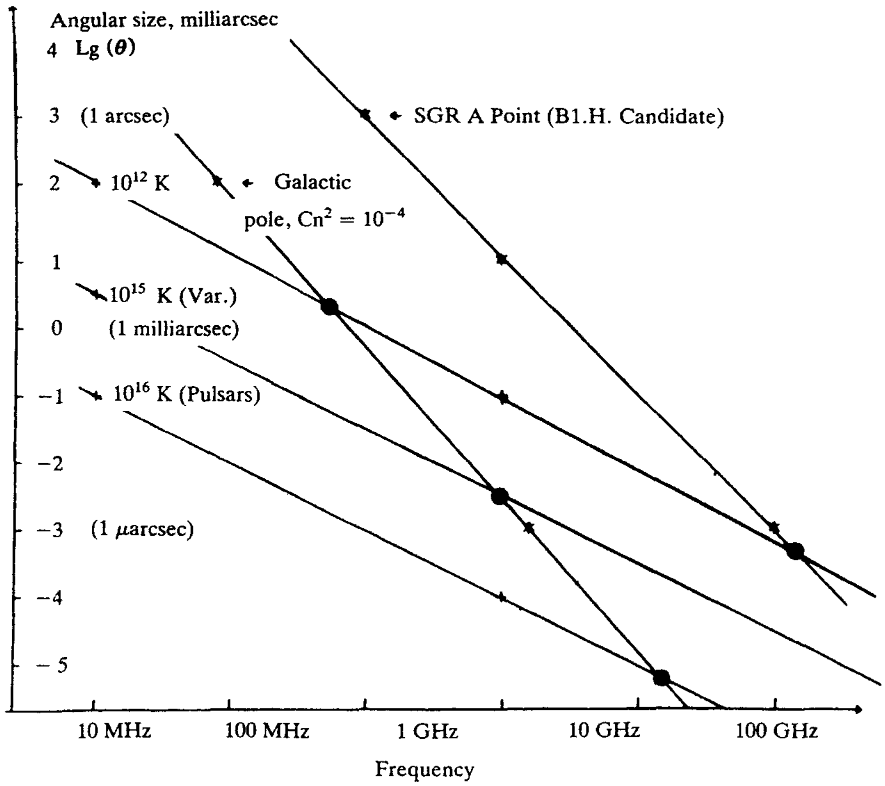

Figure 9 Scattering and Brightness Temperature Limits (IAU Symp. No. 110 results were used).

emission of radio galaxies (RG) and QSR. It was showen that for 1-Jy population of the radio sources, it gives the formal limit on the resolution of the interferometers (just $\lambda/D_{\oplus}$ where $D_{\oplus}$ is the diameter of the Earth). The main goal of Space Interferometry is to check the reality of this limit. Variable sources and pulsars can then definitely be good candidates for the Space VLBI Arrays with bases not very far from Astronomical Unit (a.u.).

Quite different limitations may appear due to very deep penetration of the Radio Astronomy, up to the epoch when radio sources were not yet born. Strong emitters will be lost first. It is visible from the very deep VLA surveys that there are no QSRs at submJy level. Tompson scattering limitation (($\tau > 1$) discussed in 60th will limit the depth of the Radio and Optical surveys. New estimates of the density of the ionized gas, and new deep (up to 29 mag.) optical surveys, change the situation. It is suggested that optical surveys may be limited by $z = 5.5$ due to the dust absorbtion, and only Radio Astronomy can go farther. 1-arcsec resolution for 21 cm (2.6 mm) redshifted lines are very important for observations of these early galaxies.

II.2 Interference Problems (Electromagnetic Pollution)

Radio Astronomy developes exponentially in parallel with the exponential development of civilization on Earth (energy and technology). This means that electromagnetic pollution will also increase exponentially. We demonstrate this point in Figure 10.

From Figure 10 we see that there is some crucial moment, after which the real sensitivity will be less than before. It means that some experiments must be realized as quickly as possible—"Now or Never!". Only the back side of the Moon can hope to escape from the "industrial limit". This problem may also be simplified by Space Radio Astronomy. Even in this case, the Radio Telescope will have to be placed at a distance from the Earth, (perhaps the most noisy planet in the whole Galaxy) a much greater distance than that of the Moon.

II.3 Conclusion

Even a quick look at the situation brings us to the following conclusions.

1. Radio Astronomy up to now has an extremely high exponential growth without any sign of deceleration in the next 25 years.

We may predict rather accurately, the expected levels, for the start of the next century, of the sensitivity, resolution, and quality of the images, and so forth.

2. Most of these parameters may be reached by the construction of the new generation of Radio Telescopes with collecting areas close to 1 million m^2, and with the arrays sizes comparable with 1 astronomical unit.

Some parameters can now be realized with existing instruments, improving receivers, software, computer facilites and image formation methods. VLA and Arecibo telescopes demonstrate how one can be on the Main Sequence of the

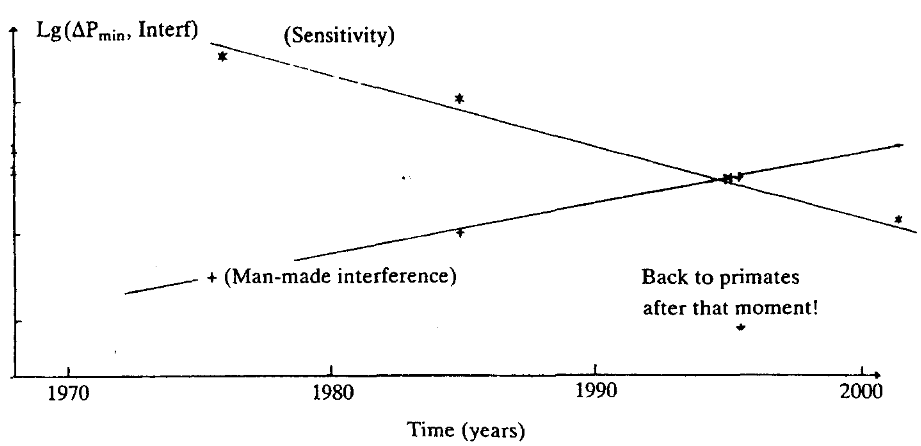

Figure 10 Interference and Sensitivity. From this Figure we see that there is some crucial moment after which pollution will shrink back the range of the visible Universe; it is like the Collapse of the human ability to understand the surrounding World with super-light speed. It is the end of HOMO SAPIENS.

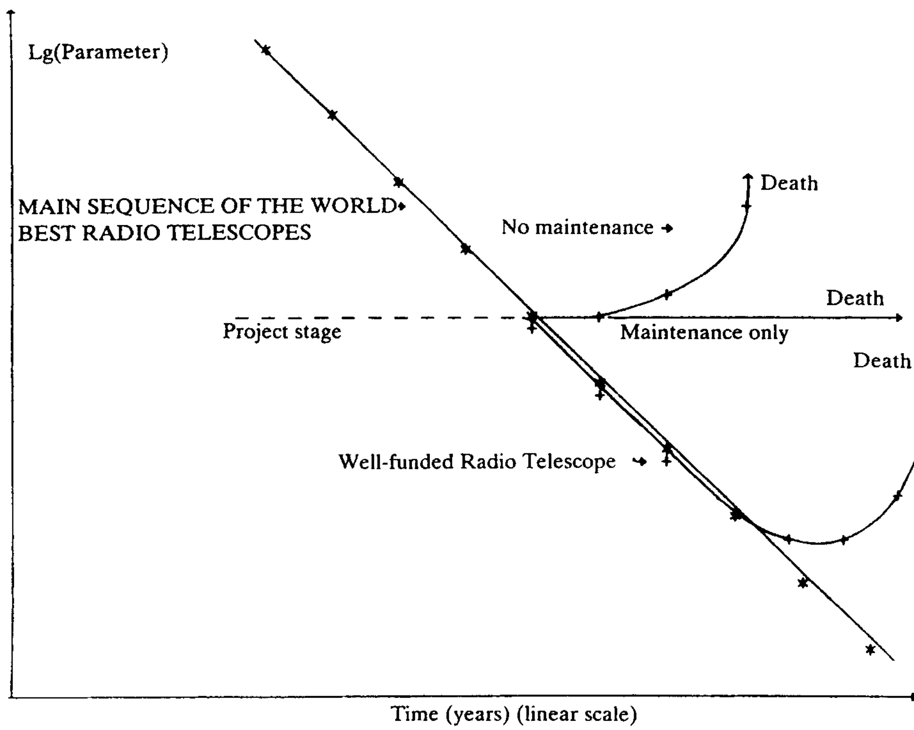

Figure 11 Evolution of a radiotelescope.

best radio telescopes for many years, in spite of the world exponential growth of the Radio astronomy potential. We reflect this situation using the analog with the star evolution process, see Figure 11.

To be on the main sequence for as long as possible, Radio Observatories spend about 10% of the construction cost of the Radio Telescope every year on the maintenance of the complex.

3. Much may be done improving the computer facilities. It may be shown that not only image quality depends strongly on the computer power but also flow of information as well. Better understanding of the image formation process, shows that up to Gain factor losses may be recovered if all information available in the Wolf Coherent function is extracted. We shall come back to this problem later. In the RATAN-600 section, losses are very important.

4. Major uncertainties for the next century Radio Astronomy are connected with scattering effects and the unknown nature of the objects.

5. IR and Optics have to be ready to use Radio methods (VLBI and so forth technique). Ten years ago, we made some suggestions in this direction, with the POLYGAN project.

III. GIANT PROJECTS (a short summary)

The first suggestion to construct 1 million m^2, and 1 a.u. size array, was made by USSR (Pulkovo group) in 1960. Below we list all of the main projects accumulated over last 25 years.

III.1 Decametric Projects

a) SPACE VLBI: 5 orbiting dipoles; 3–300 MHz (range (NASA).

b) SPACE ASTRO-ARRAY: all radio frequency range; 1000 30 m dishes at many Earth diameter distances (NASA).

c) 1 million m^2 Ground Based Array with arcsec resolution (USSR, Kharkov-Pushino-Gorkij project): 10–100 m range.

III.2 Meter-Wavelength Projects

a) Giant Equatorial Radio Telescope (GERT): 1 million m^2; arcsec resolution; 1 Jy sensitivity. A smaller version of this project is now under construction in India: 35 25 m dishes, 60 km base, VLA type configuration with central 1 × 1 km partially filled area; up to HI-frequence ($\lambda = 21$ cm).
b) See b) in item 1.
c) See c) in item 1.
d) Arcsec Synthesis Array from 10 100 m-telescopes, $\lambda = 1$ m (USSR, Pushino).

III.3 Decimeter Wavelength Projects

a) Pulkovo (1964) RATAN-type project: 20 km size; 1 arcsec resolution; 2 million m^2 area; 100 m. panels; 21 cm–1 m range; 200 mln dollars.

b) CYCLOPE project (USA): 1000 100m-dishes well packed, $\lambda = 20$ cm; CETI programme.

c) USSR (IKI) 1 km–3 km dish in Space, low orbit, dm range.

d) Japanies project of the Global Dipols Array connected with a very big computer: all sky 15-year surveys with 1 mJy sensitivity and 1 milliarcsec resolution. We have mentioned that this 1970y. project may appear again when VIDEO-NETS connecting TV and PC users are realized for communication purposes. Now there are 100 million TV-users.

e) A New (after the Moon occultation method) Interstellar Interferometry method appeared that used recently discovered 1 a.u. lenses in the ISM. Pulsar light cilinder has been resolved just now and 5 μarcsec resolution was realized. Interstellar scintillations can be broadly used.

f) Lunar-Earth interferometry may be possible if sensitivity problems can be overcome. Signals from the first Frenel zone of the moon, may interfere with the signal received by the Earth based Radio Telescope from the same source. Aperture synthesis gives good UV-coverage equivalent to the 400 000 × 70 000 km^2 dish for low declination objects. The Cornwell phase restoration method used for image plane synthesis, can also be used to convert reflected emission into the original wave front structure.

III.4 Cm-wavelength projects

a) Pulkovo cm-wavelength, RATAN-600-like ring Radio Telescope: 0.5 million m^2 area, $\lambda > 3$ cm, 1 arcsec resolution.

b) "Hubble-meter": Pulkovo 1968y project for the Space Array; 1 a.u. in size; tree of dishes for extension of the near field zone up to the Hubble radius. Direct distance measurements should be possible through the measurements of the wavefront curvature. Kardashev has shown (1972) that all cosmological parameters may be found, if the redshifts of the objects are also known.

c) "POLYGAM" project (USSR, SAO and many other): 3 70 m-dishes and 10 25 m-dishes, in collaboration with Space 30 m telescope. Three independent parts are now in progress instead of "POLYGAM": RADIOASTRON, QUASAR, and array from 3 70 m dishes, incorporated in the VEGA mission project.

d) QUASAR project (quickly developing): 10 32 m VLBI dedicated array for the geodesy and time service; $\lambda > 1.35$ cm.

e) "RADIOASTRON" project: Space VLBI; 77 000 km maximum base; $\lambda > 1.35$ cm; 10 m dish in Space; many are on the Earth.

f) "VSOP" (Japan project): 10 m dish on the 2 earth radius orbit; $\lambda > 1.35$ cm.

g) "IVS" (international project; after Radio Astron mission): 30 m dish in 200 000 km apogee orbit, $\lambda > 3$ mm.

h) 300-m Arecibo-type dish in Brazil; $\lambda > 1.28$ cm.

III.5 Mm-Wavelength Projects

a) Space ASTRO-ARRAY, see item 1,a).

b) Mm wavelength VLA-type project.

c) 70-m dish for 1 mm (USSR, first version under construction in the Central Asia, by Kardashev group).

d) 60-m dish for less than 1 mm (USA, under consideration).

e) 54-m Arecibo-type dish for 1 mm with 2.6-mm with 2.6-m on-axis optical telescope. It is almost ready in Armenia, USSR).

f) Many mm, and sub mm, dishes and arrays in the USA programme.

A very important programme of the improvement of the existing facilities to be on "the Main Consequence of the best radio telescope at the beginning of the next century" can be found in the USA Radio Astronomy programme for 1991–2010.

IV. RATAN-600 AND NEXT CENTURY

We shall now try to find the position of the RATAN-600 among the best Radio Telescopes at the start of the next century. If we could do our best to realize the potential of this unusual instrument.

IV.1 Absolute Limits

The confusion limit was calculated for different modes of operation. It is shown in Figure 12.

Highest sensitivity may be achieved at 1 cm (0.03 μJy, 0.30 μK). A good accuracy of the panels was achieved recently ($\varepsilon = 0.082$ mm r.m.s.) and we hope that active optics methods will help us to keep it at any weather conditions. It means that maximum Gain will be at

$$\lambda = 4\pi\varepsilon = 1 \text{ mm}$$

if no other sources of errors exist. At the Single Sector mode we are limited by geometrical errors (0.2 mm), but at the most powerful Zenith mode there are no such limitations and we can have about 5000 m^2 at mm-wavelengths.

Extension of the panels to 11.4 m increases the longest wavelength limit to 1 m (or 1.35 m if special big secondary mirror will be constructed). In this case we can realize 15 000 m^2 at decimeters and 10 000 m^2 at cm (see Figure 13).

Receivers are unlimited by the confusion effects even at dm decimeter waves in the Zenith mode, but not in the Flat Mirror mode (see Table 3).

Dynamical range (the ratio of the brightest to weakest features in the image) depends on the filling factor of the aperture which is better for the RATAN-600 than for VLA, limited by 1:200000 range.

RATAN-600 is limited in resolution not only by λ/D, but also by the seeing disk (about 1–2 arcsec). New, Ryle synthesis approach, gives the possibility to escape from this limit just as in the phased array systems.

Progress in the accuracy of the source position measuremenets with the RATAN-600 is shown in Figure 14. We hope that with good receivers we shall have the error box small enough for very deep identifications.

The flow of information is limited now by the sensitivity, single beam mode of operation, bandwidth, resolution, and data reduction facilities. RATAN-600 backend limitations are shown in Figure 15. We are very far from the ideal system which can extract all information from the Wolf Coherence Function of the

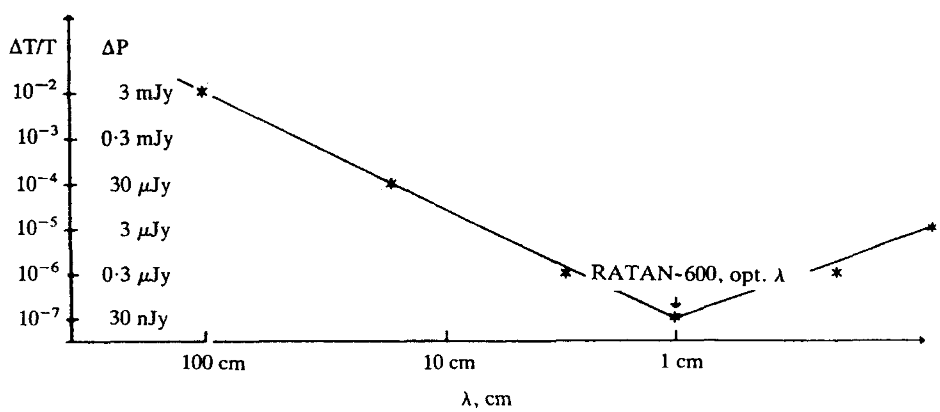

Figure 12 Absolute Radio Astronomy limit and RATAN-600 frequency range.

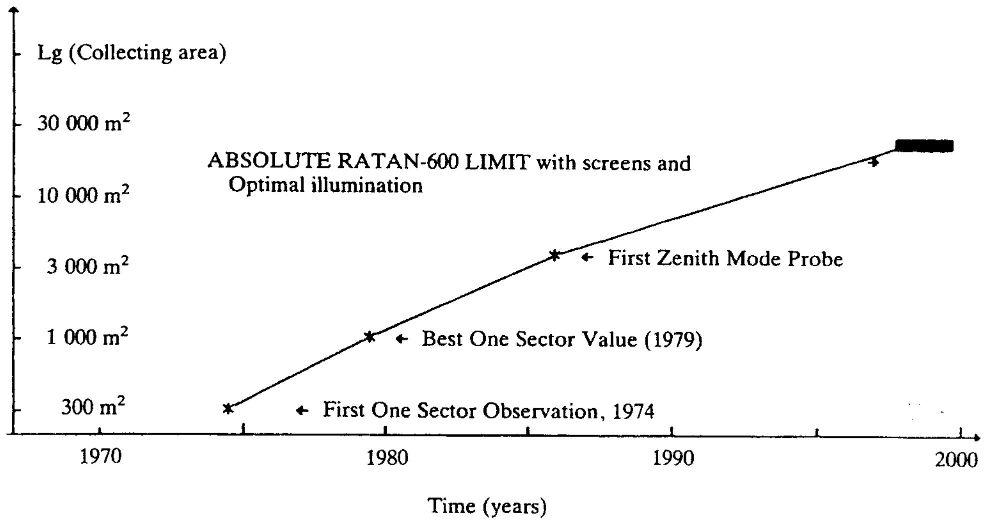

Figure 13 RATAN-600 collecting area: what we have in store.

incident radiation. In the upper right corner we show the levels which can be reached with MARK-systems. We hope that in the beginning of the next century it may be done (if necessary) at any Radio Telescope.

Now we are ready to study Table 2.

The last row shows evolution of the one source of the system temperature. Sky temperature is above 50 K at all RATAN-600 wavelengths. Table 3 shows the equivalent system temperature calculated through the dispersion of the confusion noise.

We see that the best situation is in the Zenith mode, where confusion even at

Table 2 Absolute limits on the RATAN-600 parameters.

Parameter	*Began with*	*Improved to*	*Absolute limit*	*Future Gain*
Collecting area	300 m^2	3500 m^2	15 000 m^2	4.5
Resolution	20 arcsec	5 arcsec	(0.2 arcsec)	(25)
Sensitivity	100 mJy	1 mJy	<0.1 μJy	10 000
Brightness limit	100 mK	1 mK	<1 μK	>100
Survey source number	100	10 000	>100 000 000	>10 000
Dynamical range number	1:100	1:10 000	>1:200 000	>20
Information flow	1 bit/s	1 Kb/s	100 Gb/s	100 000 000
λ_{min}	2 cm	10–3 mm	1 mm	3–10
λ_{max}	6.5 cm	31 cm	1.35 m	4
Number of beams	1–2	1–2	>10 000	>5000
Tracking time	2 s	2 min	>1 Day	>700
Ground radiation	(70 K)	5.5 K	<1 K	5.5

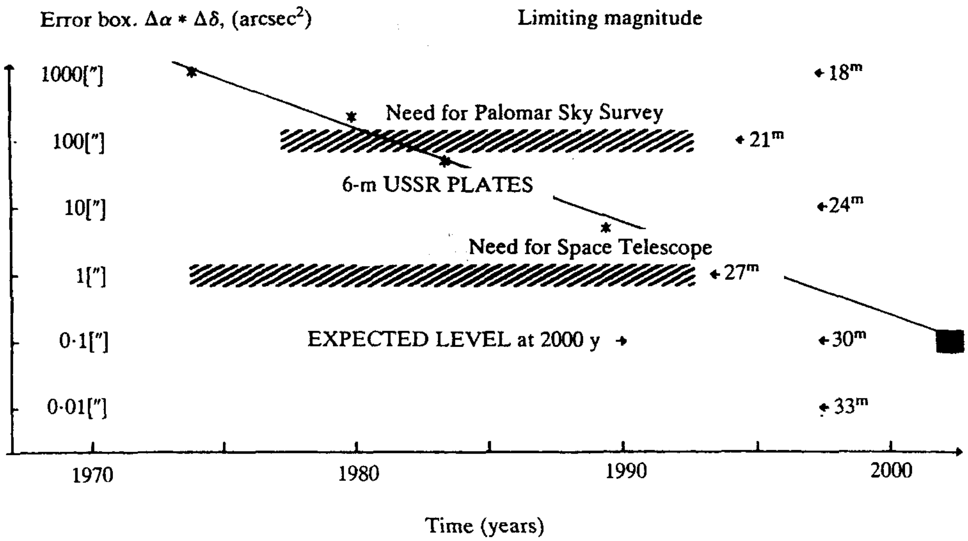

Figure 14 Evolution of the "Error box" of the position measurements at RATAN-600 and the deepness of the optical identification (left, Y-axis).

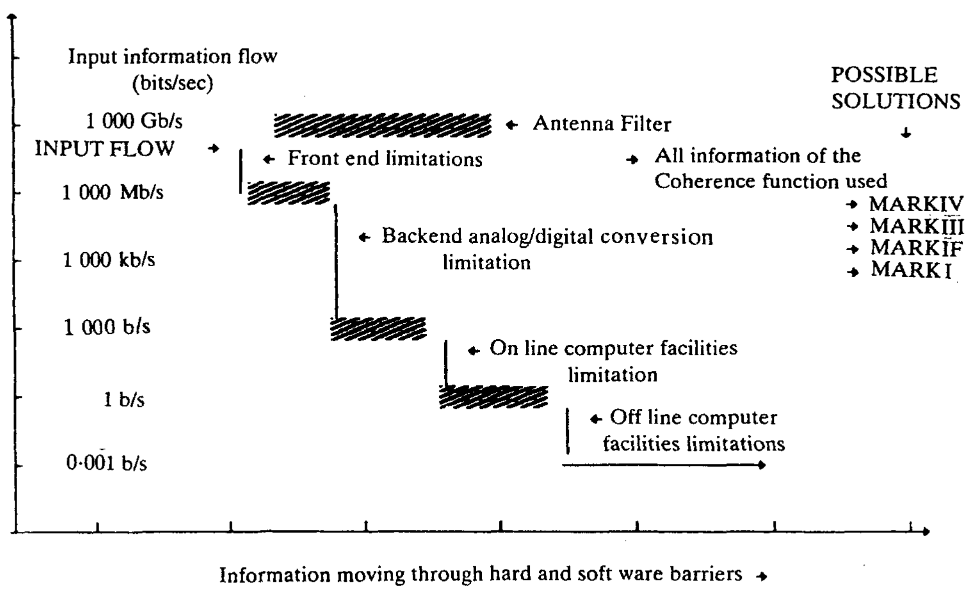

Figure 15 RATAN-600 and Backend limitations.

Table 3 Equivalent confusion system temperature.

λ cm	*Flat mirror mode*	*Single sector mode*	*Zenith mode*
135	200,000 K	40,000 K	600 K
75	60,000 K	12,300 K	170 K
31	5000 K	1000 K	12 K
13	500 K	100 K	1.2 K
7.6	110 K	22 K	<1 K
6	60 K	11 K	<1 K
3.9	22 K	5 K	<1 K
2.7	7 K	1.5 K	<1 K
1.3	<1 K	<1 K	<1 K

the longest possible wavelengths gives only small contribution to the Sky temperature (Milky Way region at least). Contribution of the spillover radiation to the system temperature of the RATAN-600, versus time, is shown in Figure 16. It evolved very quickly, and there are no limits to use the best receivers, at least at cm wavelengths.

IV.2 RATAN-600: Not Realized Suggestions

1. *Flexibility of the geometry*

   a) Multy-beam operation for strong sources.

   b) Eschelet-type observations (greater resolution at low elevations, spectroscopy).

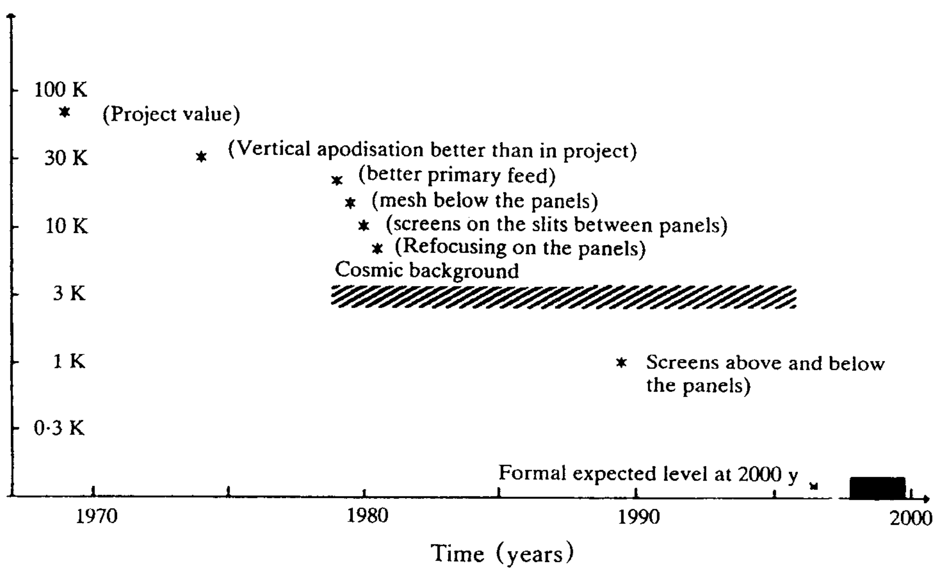

Figure 16 RATAN-600, Ground Radiation component of the System temperature versus Time (Spillover effect); $\lambda < 6$ cm.

c) Inter-sectors interferometry.

d) Changing of the concentration of the light from zero order to the given one for spectroscopy and for multy-frequency tracking.

e) Extension of the "Estafeta" method to the full day tracking using "virtual telescope" approach.

f) "Running parabola" method for 4-24 tracking (depends on Dec.).

g) Near-pole multy-days tracking using present day facilities.

h) J^2 synthesis equivalent for Zenith mode.

j) Fouries spectroscopy with moving panels.

k) Self-calibration of the position of the focal point.

l) Active optics approach.

m) Automated methods of the panels adjustment.

2. *Upgradings. Antenna*

a) Mm-wavelengths activity.

b) Long-dm, m-wavelength activity.

c) Full-tracking solution.

d) Deep cooling of the RATAN-600 by mesh.

e) From reflector-type to phased-array type imaging.

f) Secondary mirror solutions: auto-positioning, tracking and so forth.

g) Close to 80–90% efficiency with 3-mirrors solution.

h) Special mm-, dm-, m-secondary mirrors with proper underillumination at mm and phase corrections for dm and m.

3. *Upgradings. Receivers and backends*

a) Matrix type feed array.

b) Receivers with $T_{receiver}$ below the sky temperature.

c) Panorama-type all-frequency range system.

d) From multy-data aquisition system to single (main building) system with fibro-optic connections with secondary mirrors.

e) Data-reduction in the real time (spectra, catalogs and so forth).

f) Digital lines to main office facilities, to computers nets, to the users).

g) Remote mode of operation.

h) Filtration of interferences of all kinds (hard and software solutions).

i) All Stokes parameters system with less than 0.1% instrumental errors (hard and soft-ware solutions). All sensitive receivers have to be equipped by L and R polarimetry receivers.

j) Dikij-type feeds for zenith-mode, tracking, array-feed (?).

k) Pulsar- and Solar millisecond backends.

l) VLBI-terminal (when tracking problems will be solved, or when sensitivity will be adequate to the VLBI transit survey).

IV.3 Guiding Problems to be Solved (Suggested by Users)

1. *Sun*

a) Full disk, all day, all Stokes parameters, all frequency range with μ second time resolution (3-dimensional mapping +time).

b) "Stilsread"-type programmes for Solar-Earth problems.

2. *Planets*

a) Moon: 3-dimensional mapping at longest up to shortest wavelength.

b) Having good receivers (and tracking) planets satellites may be explored as our Moon.

c) Accurate temperature and position measurements of the Mercuri, Mars are waiting for better time.

3. *Galaxy*

a) Radio Stars (multy-frequency patroling).

b) Pulsars: survey; millisecond-time keeping.

c) Continuum, spectral lines, polarisation, two-dimensional mapping of the Milky way.

d) Small (and large) scale irregularities of the interstellar medium with small brightness temperature contrasts.

e) Variable stars and objects (as Sgr-A point source).

4. *Metagalaxy*

a) All-Sky surveys (later-shorter wavelengths).

b) Deep surveys of the selected regions. Accurate position measurements. Identifications.

c) Active galactic nuclei programme (multy-frequency patrol, spectrum-structure programme, polarized remnants of activity and so forth).

d) Search for variable sources at different flux density level.

e) Clusters of galaxies; SZ-effects; Steep spectrum sources.

f) Radio source clustering; Void-structure.

g) Two-dimensional mapping of the selected regions (cold strip, zenith strip, near-pole region, and so forth.

5. *Cosmology*

a) Log N–Log S, cosmological evolution of the Radio Activity in galaxies.

b) $\Delta T/T$: discovery, mapping and BIG COSMOLOGY.

c) H- and CO-lines Forest programme.

d) Spectral irregularities of the 3 K background.

e) Search for most distant objects (including IR-Radio programme).

We see that only a very small fraction of the potential of the main USSR radio telescope, RATAN-600 was realized. We estimate that even with 10% funds (from the capital investment in the construction of the RATAN-600 in the current rubles) every year, that is with minimal international standard funds, it is possible to be on the Main Sequence of the Best World Radio Telescopes in the next 15-25 Years. Some very important improvements are needed in the extra grants: mm-wavelength full operation, Ryle synthesis mode of image formation, full day tracking mode, and broad band connections with computer networks and users.

Below we list the directions of the activity where RATAN-600 can compete with world Radio Astronomy at the beginning of 21st century, and where RATAN-600 can help to fill the gap between the dishes and arrays.

IV.4 RATAN-600 and High Priority Directions of Modern Astronomy

1. As the reflector type of the radio telescopes, all kinds of observations where a very broad frequency range (multy-colour radio photometry) is needed, are of the highest priority. Out of the competition are all-frequency range problems such as very deep redshift surveys.

2. Low brightness searches are available for RATAN-600, because it is reflector. We demonstrated this in some researches of radio galaxies, and in the 3 K emission observations. RATAN-600 is better than usual reflectors (full dishes) because of much stronger confusion limitations in the later case.

3. Big "dayly field of view" in the transit mode of operation of RATAN-600 make this instrument very efficient for survey types of observations. Real efficiency depends strongly on the sensitivity of the Radio Telescope in this (small integration time) mode of operation. The best result may be reached if the single dayly scans are dominated by confusion noise, but not by a receiver one. Confusion noise is very small due to the unusual geometry of the RATAN-600. It is also important to note that the RATAN-600 frequency range includes the point of the absolute minimum of the combined Radio-Infrared confusion noise that was computed recently using IRAS, and very deep VLA data (about 1 cm, see number 4 below).

4. As an aperture synthesis instrument, RATAN-600 is out of the competition for the mapping of radio scales that are too big for VLA-type systems but too small for parabolic dishes. In principal, the dynamical range (the quality of the images) of such maps may be much better than in the VLA case, due to a much greater filling factor of the aperture. Up to now we have not realized this advantage of the RATAN-600 (no software, no adequate computer facilities), except in the one-dimensional case.

IV.5 Radio Astronomy in Spectral Astrophysical Observatory—North Caucasus

At North Caucases the 6 m optical telescope, and RATAN-600 are the main Ground Based facilities of the USSR. More than 600 people are on staff, and a big intellectual potential was accumulated during the last 15 years. More than 80% of cm- and dm-results in Radio Astronomy of the USSR, and almost all extragalactic research in optical astronomy of the USSR, were made with the help of these instruments and staff.

In 1979 we suggested the addition of new, complimentary facilities to RATAN-600. They included:

1. 128 m-dish for VLBI and spectroscopy, and so forth.
2. 20 m-dish for mm-wavelengths molecular spectroscopy.
3. 1 million m^2 Pulsar field array.
4. Aperture synthesis array connected with RATAN-600.

Some suggestions are moving rapidly. There is the very big dish project, which greatly increases the efficiency of the USSR National dedicated array (QUASAR), aw well as the efficiency of the Space Mission. The World's Biggest dish will be very popular in all international Radio Astronomy activity.

It is well known that the cost of a big Observatory (in any country) is greater than the capital investments. It is also known that the stability and efficiency of the Observatory is much higher if there are different kinds of instruments that can react quickly to the changes of intellectual interests.

This is why we believe that we should discuss, not only the solutions to problems, but also perspectives on new facilities.